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Payback period for residential solar water heaters in Taiwan

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A B S T R A C T

Taiwan is a leaf-shaped island straddling the Tropic of Cancer with abundant and reliable supply of solar energy. Under the individual circumstances (solar radiation, ambient temperature and hot water consumption pattern), solar heating could be economically competitive with conventional heating fuels (electricity, natural gas or liquefied petroleum gas). In this context, the market of residential solar water heaters (SWHs) in Taiwan has been highly developed with subsidy programs offered by the government of Taiwan so far. Next, the economic viability of residential SWHs is determined by the life-cycle savings. This study develops a procedure for estimating the payback period of residential SWHs in terms of operation cost and effective energy savings over conventional heating fuels. A case study in southern Taiwan indicates that the increase in daily load volume per area of solar collector installed has a beneficial effect. An end user should determine the economically optimal solar collector area of an SWH according to the hot water consumption pattern of each household. Payback period is shorter when the substituted conventional fuel is electricity. With the subsidy program, an SWH is in a favorable situation when compared with an electrical water heater. Findings of the present study would assist partially system design of residential SWHs and help accrue more monetary benefit to the end users.

Contents

1. Introduction

Renewable energy is receiving increasing support due to its environmental advantages, and solar thermal applications have been acknowledged among the leading alternative solutions. SWHs have proven to be cost efficient for both domestic and industrial applications [1]. Taiwan has depended almost exclusively on imported fossil fuels to fulfill its energy needs. The ratio of indigenous energy to total energy supply in Taiwan was 2.1% in 2011 [2]. Other than the issue of global climate change [3], the use of renewable energy is critical in national economic development. Significant efforts have been made toward the development and dissemination of biomass energy, geothermal energy, ocean energy, photovoltaic energy, solar thermal energy and wind power generation in Taiwan during the past two decades [4–7]. For solar thermal energy, SWHs, which can provide hot water at

Abbreviations: BEMOEA, Bureau of Energy, Ministry of Economic Affairs; CPI, consumer price index; EWHs, electrical water heaters; GWHs, gas water heaters; LPG, liquefied petroleum gas; LNG, liquefied natural gas; SC, solar collector; SWHs, solar water heaters

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Nomenclature

A_{sc}	area of solar collector installed
C_n	operation cost
E_{ei}	actual daily solar energy gain
E_i	daily available solar energy
E_o	net annual heat output
G	solar radiation per square meter
g_m	inflation rate
IC_o	initial cost
L	daily load volumes
m	annual maintenance cost
n	years of operation
Q_i	daily energy demand for hot water production
R_n	total savings

Greek symbols

ΔIC	difference in operation cost
η	thermal efficiency
γ	subsidy ratio as a percentage of initial cost

temperatures ranging from 40 to 80 °C, for domestic or industrial use,
are one of the most common applications. With the subsidy programs offered by the Bureau of Energy, Ministry of Economic Affairs (BEMOEA) and some regional governments, the accumulated area of solar collectors installed at the end of 2011 reached 2.13 million square meters [8].

Srinivasan [9] pointed out that a national renewable energy policy is a vital prerequisite for translating customer choice into a larger market share for non-conventional energy technologies. Financial incentives have been adopted for SWHs in many countries, including direct subsidy, performance-based subsidy, tax credits and tax deduction [10]. According to the statistical data gathered by the Taiwan Gas Appliance Manufacturers Association [11], gas water heaters (GWHs, 73.8%) dominated the market while the market share of electrical water heaters (EWHs) was 23.5% in 2011. There are approximately 0.3 million residential SWHs in operation, which represents less than 4% of the total households [12]. Most of the SWHs use natural circulation. Further, the capital cost of SWHs is considerably higher than that of GWHs or EWHs. Even with the national and regional subsidy programs [13,14], financial consideration is the key determinant in the decision process of consumer adoption. For residential SWHs in Taiwan, the average area of solar collector installed (A_{sc}) is approximately 5 m^2 and 3 m^2 (4- to 6-person household) for flat-plate type and evacuated-tube type solar collectors, respectively. The ratio of volume of storage tank to A_{sc} ranges from 50 to 80 l/m^2 [8]. Furthermore, as a rule of thumb for the system design of an SWH, the daily hot water consumption for each person corresponds to the hot water production of $A_{sc} \approx 1$ m^2. Therefore, an SWH with A_{sc} less than 2 m^2 would be used for one- or two-person households.

A residential SWH system could reduce water heating energy demand by 50–85% [15]. Payback period might be 2–4 years, depending on the type and size of the system [16]. However, the economic feasibility of SWHs is mainly determined by their initial cost, long-term efficiency and subsidy program. Islam et al. [1] demonstrated that the installation of SWHs are more feasible on a large A_{sc} compared to a small unit installed per household in terms of energy conservation and per unit energy cost over initial costs. For residential SWHs, Pan et al. [17] indicated that the payback period of SWHs in Taiwan varies from 6 to 15 years in different regions and type of heaters being replaced. However, other than the climatic conditions, the A_{sc} of a system and hot water use pattern are also among the dominant factors influencing the payback period of an SWH. In this study, the payback calculation model developed by Kaldellis et al. [18] is adopted. The operation cost of an SWH comprises its initial and maintenance costs. The annual inflation rate, taken as the consumer price index (CPI) in this study, is also taken into account. For the benefit part, the collector efficiency, effective solar radiation and hot water consumption pattern are included.

The remainder of this paper is organized as follows. Section 2 provides a brief description of the payback model. The climatic condition (global solar radiation and ambient temperature) in southern Taiwan, collector efficiency and hot water consumption pattern are employed to evaluate the effective heat gain. The historical prices of the conventional fuels (electricity, natural gas and liquefied petroleum gas) are also given. The payback period is obtained by the sensitivity analysis of major variables (unit price of a SWH, daily load volume and fuels being substituted). To consider a choice between SWHs and EWHs for an end user, economic costs of the heaters are addressed in Section 3 and conclusions are drawn in Section 4.

2. Payback period of SWHs in Taiwan

To assess the economic feasibility of SWHs in Taiwan, the payback calculation model developed by Kaldellis et al. [18] is adopted to estimate the operation cost (C_n) and total savings (R_n) due to the thermal energy offered by an SWH after n years of operation, in which

$$C_n = IC_o\left[(1-\gamma)+m\frac{1+g_m}{g_m-1}\left[\left(\frac{1+g_m}{1+i}\right)^n-1\right]\right] \quad (1)$$

where IC_o is the initial cost of an SWH; γ is the subsidy ratio as a percentage of IC_o; m represents the annual maintenance cost (=2% of the initial cost in this study, according to a general survey on local installers in Taiwan); g_m is the inflation rate; and i is the local annual capital cost.

$$R_n = E_o c_o\frac{1+e}{e-i}\left[\left(\frac{1+e}{e-i}\right)^n-1\right] \quad (2)$$

where E_o is the net annual heat output of an SWH; c_o is the present value of the effective cost coefficient of the substituted conventional energy; and e is the mean annual rate of price change in the substituted conventional energy.

2.1. Cost analysis

This analysis involves the initial and maintenance costs of a system, which are calculated using market data. For SWHs in the domestic sector, the mean annual rate of CPI (=1.38% from 2004 to 2011) and the average one-year interest rate of saving account (=0.949% from 2009 to 2011) are deemed suitable for representing the inflation rate and local annual capital cost, respectively [19]. Furthermore, the glazed flat-plate-type solar collectors with metal absorbers and glass cover are widely used in Taiwan. The average unit price (2009–2011) is 9100 and 14,000 NTD/m^2 (NTD: New Taiwan Dollar) for a system with $A_{sc} < 2$ m^2 and A_{sc}=4–6 m^2, respectively, as shown in Fig. 1. With the similar thermal output per A_{sc}, a shorter payback period can be expected for an SWH of

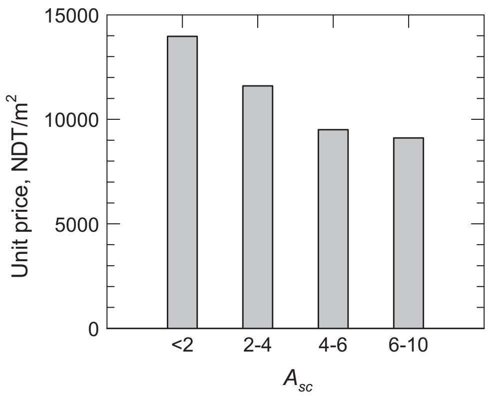

Fig. 1. Average unit price of SWHs (2009–2011) in terms of A_{sc}.

larger scale. This also explains partially the limited installation of residential SWHs with $A_{sc} < 2\ m^2$ [12]. In addition, the current subsidy program offered by the government of Taiwan was initiated to promote utilization of SWHs in 2000. By filling an application form, end users will be granted a subsidy according to the area and type of solar collectors installed (2250 NTD/m^2 for glazed flat-plate and evacuated-tube solar collectors, and 1500 NTD/m^2 for unglazed flat-plate solar collectors). Thus, γ ($\approx$ 16–25%) is dependent on the scale of a system. Further, the time allocation of the cost over the life cycle of a system is of interest. One may examine C_n as a function of service period of the installation, for SWHs with IC_o=8000–16,250 NTD/m^2. With the current subsidy program offered by the BEMOEA, C_n=9100–20,800 NTD/m^2 with the system operating for 20 years. Then the data are employed to compare the annual benefit of an SWH and to determine the payback period.

2.2. Benefit analysis

Although there are environmental benefits from SWHs, they are not easy to measure in monetary terms. Thus, the present study focuses mainly on the reduction in consumption of conventional fuels. Emphasis is placed on economic pricing so that an end user can take rational decisions in cost-effective energy alternatives. Then as mentioned above, GWHs and EWHs are the most common methods of producing hot water in Taiwan. The changes in market price of conventional fuels during the last decade are shown in Fig. 2 [2]. As can be seen, the annual price of LNG and LPG increased almost linearly, while the variation in price of domestic electricity was rather limited due to government intervention for controlling inflation. To calculate the effective cost of the substituted conventional fuel, the fixed price change is adopted in this study instead of a fixed ratio in the payback calculation model by Kaldellis et al. [18]. The mean annual price change is 0.08 NTD/kWh, 0.98 NTD/m^3 and 1.5 NTD/kg for electricity, LNG and LPG, respectively. The local market annual capital cost is also taken into account to estimate the revenue from the SWH investment.

To estimate the annual heat gain of an SWH, one should take into consideration daily solar radiation and hot water consumption pattern per person. According to CNS 12558-B7277, the amount of collected solar energy divided by the total energy incident on the collectors (thermal efficiency, $\eta = \dot{m}C_p(T_{out,i} - T_{in,i})/(A_{sc}G)$), where C_p is specific heat; G is daily solar radiation per square meter; $T_{out,i}$ and $T_{in,i}$ are the final temperature and initial temperature in the water storage tank, respectively. The monthly solar radiation per square meter in Taiwan is shown in Fig. 3 [20]. It can be seen that summer radiation (less hot water required) is sufficiently higher than that from November to February (high demand). Thus, the hot water

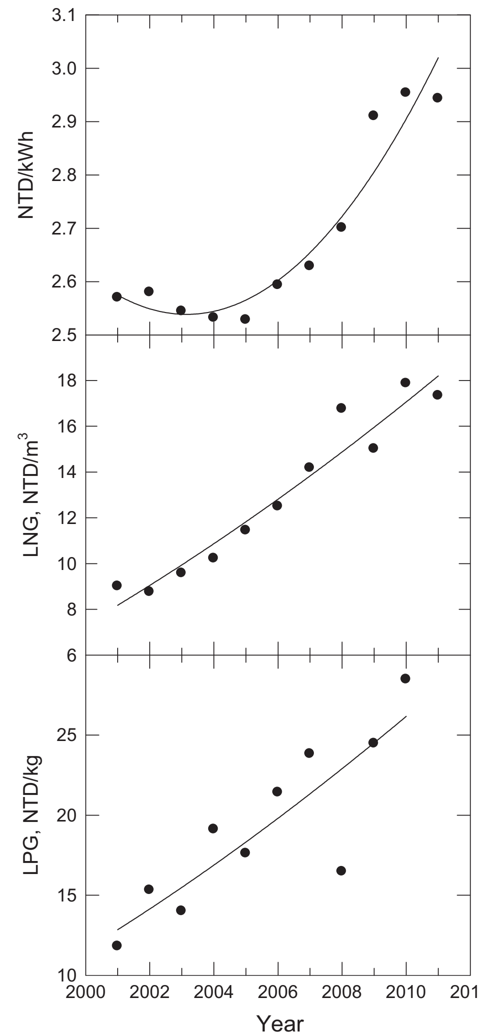

Fig. 2. Prices of conventional fuels.

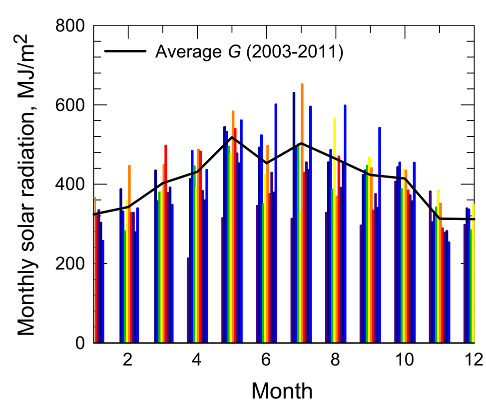

Fig. 3. Monthly solar radiation per A_{sc} (2003–2011).

available normally exceeds the corresponding demand of end users in summer. Measured real performance of residential SWHs can be lower than expectations [21]. The benefit analysis using total annual solar radiation would overestimate energy savings. Pan et al. [17] proposed the method of effective solar radiation. With η=0.5, potential heat output of an SWH is estimated according to tap water temperature and solar radiation. However, it is known that there are considerable energy heat losses from the hot water storage tank,

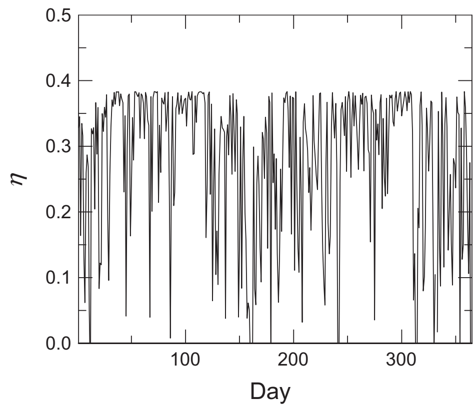

Fig. 4. Daily variation in thermal efficiency of an SWH in 2011.

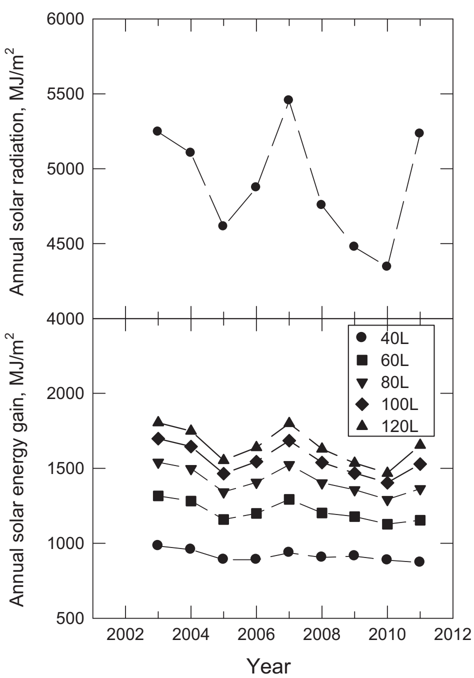

Fig. 5. Annual solar radiation and solar energy gain.

especially at lower ambient temperature. According to the field measurements, Lin et al. [22] indicated that η of a dormitory system decreases significantly when the daily solar radiation per square meter is less than 7 MJ/m^2. In this study, η is taken as a function of daily solar radiation per square meter.

In Taiwan, the average daily solar radiation per square meter is 3.25 kWh/m^2 in the north and 4.64 kWh/m^2 in the south [2]. Therefore, there are about 140,000 SWHs installed in southern Taiwan (55% of total SWHs installed in Taiwan) during the last decade [8]. This case study assumes that an SWH is installed in Taiwan, covering the hot water need of a family of one to six persons. The daily available solar energy E_i is calculated according to the daily solar radiation and η. Example of variations in daily η in 2011 is shown in Fig. 4. As can be seen, η is not necessarily higher in summer than in other seasons. Further, the domestic hot water load profile is associated with hot water consumption pattern per person and family size. A distribution of hot water consumption with a maximum in winter and a minimum in summer due to changes in the cold water temperature over the year and due to the behavior of inhabitants can be expected [23]. The solar energy gain per A_{sc} can be estimated using on daily solar radiation, η, ambient temperature and hot water consumption pattern per person. Note that the typical hot water consumption per person (tap water temperature = 42 °C) ranged from 40 l/day to 80 l/day in Taiwan [24].

As mentioned above, extra solar radiation cannot provide additional energy savings. The formula for estimating actual daily solar energy gain E_{ei} can be expressed as

$$E_{ei} = \min\{E_i; Q_i\} \tag{3}$$

where Q_i is the daily energy demand for hot water production. Kaldellis et al. [18] indicated that the available hot water normally exceeds the corresponding demand during the hot season period ($E_i > Q_i$, $E_{ei} = Q_i$). During the cold season months, an SWH may not fulfill the daily hot water demand of the end users ($Q_i > E_i$, $E_{ei} = E_i$).

The yearly solar radiation from 2003 to 2011, ranging from 4350 to 5450 MJ/m^2, is shown in Fig. 5. It can be seen that there is a large variation. The effective annual solar energy gain is then calculated based on the daily hot water consumption pattern. As a rule of thumb for system design of an SWH in Taiwan, the daily hot water consumption for each person corresponds to the hot water production of $A_{sc} \approx 1$ m^2. For daily load volumes L of 40–120 l, the annual solar energy gain per A_{sc} (L/A_{sc}) ranges from 915 ± 4% (40 l/day) to 1647 ± 7% (120 l/day) MJ/m^2. The lowest performance is associated with the smallest daily load volume, which is consistent with the study by Haralambopoulos et al. [25]. Note that the effective annual solar energy gain divided by the amount of

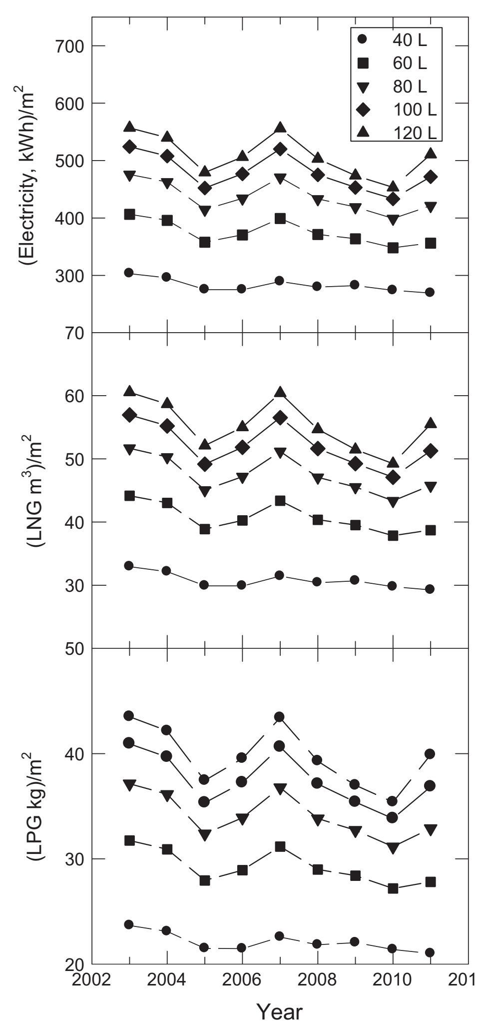

Fig. 6. Daily load volumes per A_{sc} on fuel being substituted by solar energy.

collected energy of solar collectors is from 50% to 89%, indicating that larger daily load volume may facilitate the system economics.

The heating value and the heating efficiency for electricity are 3.60 MJ/kWh and 90%, respectively. The heating values for LNG and LPG are 37.24 MJ/m^{3}and 51.83 MJ/kg, respectively [2] while their heating efficiency is 80% [17]. Fig. 6 shows L/A_{sc} (=915–1647 MJ/m^2) on fuel being substituted by solar energy during 2003–2011. It is obvious that there is a reduction in consumption of conventional fuels with increasing daily load volume. For example, reduction of electricity by an SWH ranges from 282 ± 4% to 508 ± 7% kWh per A_{sc}. Furthermore, one may examine R_n as a function of service period of the installation. The benefit with three fuels being substituted under different L/A_{sc} is calculated, as shown in Fig. 7, revealing the benefit associated with L/A_{sc} and the fuel being substituted. For example, the monetary benefit with 20-year service period and the substituted fuel of electricity is 18,600–31,600 NTD/m^2 with L/A_{sc}=915–1647 MJ/m^2. For system economics, it is clear that larger L/A_{sc} and electricity being the substituted fuel would be preferred.

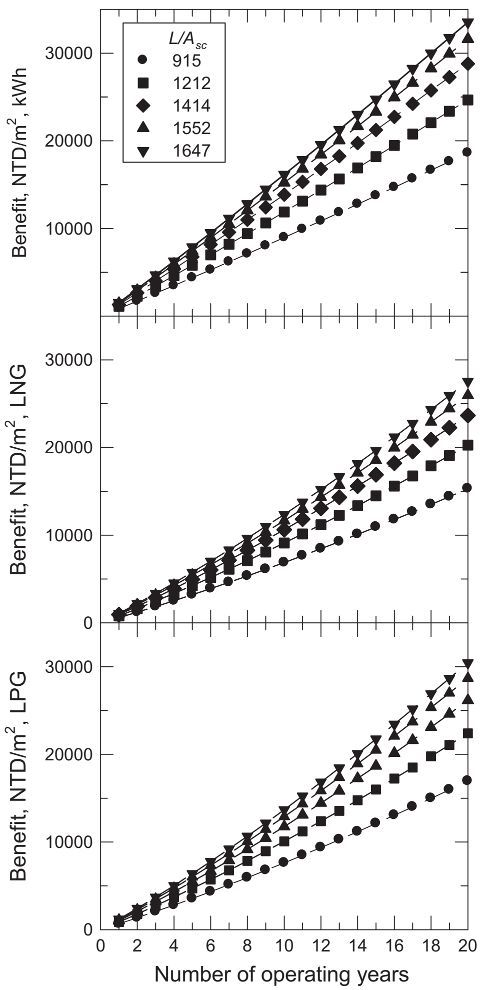

Fig. 7. Benefits with reduction in consumption of conventional fuels.

2.3. Sensitivity analysis

As shown in Fig. 5, the annual solar energy gain from 2003 to 2011 for a given daily load volume is roughly the same. Therefore, the dominant factors on the payback period of SWHs are operation cost, subsidization, daily load volume and type of substituted fuel. Further, the payback period is defined as the time required for the cumulative fuel savings to equal the operation cost. For L/A_{sc}=1212 MJ/m^2 (or 60 l/day), the payback period as a function of unit price of an SWH, as can be deduced from Figs. 6 and 7, is shown in Fig. 8. It can be seen that the payback period (5.6–21.1 years) depends on the type of substituted fuel and increases linearly with the unit price of an SWH. Since the service period of an SWH is estimated roughly to be about 15 years in Taiwan, no SWHs are financially viable with IC_o=16,250 NTD/m^2. Moreover, introducing SWHs appears least feasible when the substituted fuel is LNG. Then under the current national subsidy program ($\gamma \approx$ 16–25%) in Taiwan, it is possible for an end user in Taiwan to cover the annual hot water needs by using an SWH instead of a conventional GWH or EWH. However, the corresponding investment is marginally viable when $IC_o \geq$ 12,000 NTD/m^2, in which the calculated payback period exceeds 10 years.

As mentioned above, the effective annual solar energy gain depends on the daily load volume. In Fig. 9, the effect of L/A_{sc} (IC_o=10,000 NTD/m^2) on the payback period is presented. For L/A_{sc}=915 MJ/m^2, an SWH is least utilized. The corresponding payback period exceeds 10 years for all three types of substituted fuel. With increasing L/A_{sc}, there is a downward trend and the effect of the type of substituted fuel is less significant, in which the payback period ranges from 5.6 to 7.4 years with L/A_{sc}=1647 MJ/m^2. The performance is almost double the value for that of L/A_{sc}=915 MJ/m^2. Therefore, there is a beneficial effect with larger daily load volume. Then taking into account the financial attractiveness of an SWH, the common system design with $A_{sc} \approx 1$ m^2 for each person needs to be re-evaluated. An end user should determine the economically optimal solar collector area of an SWH according to the hot water consumption pattern of each household.

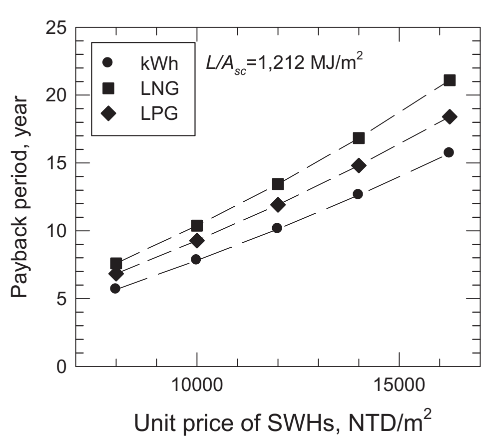

Fig. 8. Payback period as a function of unit price of SWHs, L/A_{sc}=1212 MJ/m^2.

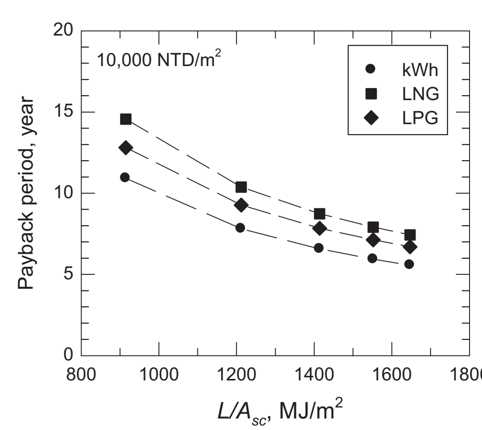

Fig. 9. Payback period as a function of L/A_{sc}, IC_o=10,000 NTD/m^2.

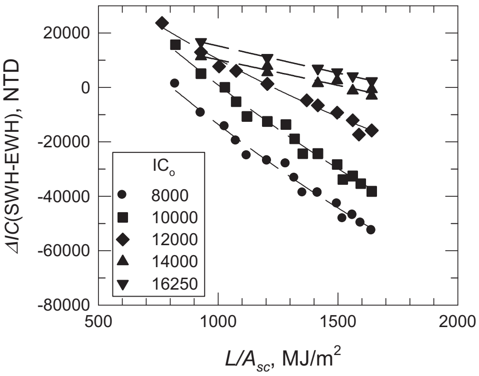

Fig. 10. Solar water heater vs. electrical water heater, 10-year service period.

3. SWHs versus EWHs

As mentioned above, electricity being the substituted fuel would be preferred in Taiwan. Further, almost all residential SWHs have an electrical booster element installed as a backup heating system, and the electricity price has recently increased. Therefore, one may compare the present solar hot water production cost with the corresponding cost when using an EWH. According to the statistical data by the TGAS, the initial cost of a 55-l (12 gal) EWH is roughly 12,500 NTD, and the service period is assumed to be 8–10 years. Then the choice of different alternatives in hot water production would depend on the operation cost of an SWH and the price of electricity. The break-even analysis is employed to study these two alternatives for an end user [26], assuming no subsidization for an EWH. It is better to install an SWH when the operation cost of an SWH is lower than that of an EWH. Fig. 10 shows the difference in operation cost (ΔIC) between an EWH and an SWH. For a service period of 10 years, the break-even point corresponds to $\Delta IC=0$. The results indicate that ΔIC decreases with higher L/A_{sc} for different initial costs of an SWH. It is also seen that ΔIC is positive for $IC_o \geq 14{,}000$ NTD/m^2, in which an SWH is not in a favorable situation when compared with an EWH. With lower IC_o and higher L/A_{sc}, there is a downward trend in ΔIC. An SWH will become more financially attractive. In other words, an SWH of larger scale and with higher daily load volume will accrue more monetary benefit to an end user.

4. Conclusions

Economic feasibility of SWHs is associated with payback period. The impressive diffusion of SWHs in Taiwan during the last two decades has been due to the national and regional subsidy programs. However, the daily load volume also plays an important role in proper sizing an SWH. The economically optimal solar collector area of an SWH should be calculated according to the hot water consumption pattern of each household. This paper evaluates the payback period of residential SWHs in southern Taiwan. For a service period of 15 years, it is clear that an SWH covering the hot water need of a family of four to six persons, with lower initial cost and higher daily load volume, can compete with a GWH (LNG or LPG) and an EWH. Therefore, proper sizing of an SWH would definitely make its adoption more financially attractive. The common system design with $A_{sc} \approx 1$ m^2 per person needs to be re-evaluated. The break-even analysis was also conducted between an SWH and an EWH. For a service period of 10 years, an SWH with $IC_o \geq 14{,}000$ NTD/m^2 is not in a favorable situation when compared with an EWH; hence, the subsidy program is critical to the dissemination of SWHs in the domestic sector.

Acknowledgments

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